

RADIATION TESTING OF LINEAR MICROCIRCUITS

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ABSTRACT

A study was made to determine the effects of fast neutron radiation on linear microcircuits. Both overall effects and individual components were studied. Circuits tested were two operational amplifiers and two gold-doped comparators. The primary results of the tests were that one operational amplifier and the gold-doped comparators withstood up to 10^{14} nvt. The other operational amplifier withstood at least 3×10^{13} nvt. At these levels, gain was down about 50 percent on the comparators and input bias current was doubled. On the operational amplifiers, the input current showed a more severe degradation than did the gain, because more feedback was used. Other circuit parameters showed little significant change up to the levels at which the gain was halved. By measuring common-base, current-gain degradation at different current levels, it is shown that both base transport factor and emitter efficiency degrade with radiation. It has been determined that diffused resistors show little change up to 10^{15} nvt. Since circuit design utilizes resistor ratios instead of absolute values, the effect is further reduced. Avalanche breakdown voltages increased due to higher resistivities, as expected. The performance changes in other components were negligible.

A particularly interesting aspect of the study was to determine the sensitivity to radiation of a wide-base device, the so-called lateral PNP. Tests showed that the device was more sensitive to radiation than the NPN structures. Betas decreased by an order of magnitude at 3×10^{13} nvt. A vertical PNP also showed heavy degradation.

Correlation is given between the above component changes and the overall circuit performances. It is shown that the overall gain can be made practically independent of beta. The voltage offset and current offset proved to be mostly unaffected by radiation up to 10^{14} nvt. Since the collector currents of the input stage are constant, the input bias current correlates directly to beta.

INTRODUCTION

Since linear microcircuits are now being used in a number of space and defense applications, it was deemed advisable to determine the radiation resistance of the linear microcircuits produced by Fairchild. It was decided to test for permanent damage due to fast neutrons in the first part of the program. Units were tested at Fairchild and then sent to Northrop for radiation with fast neutrons of energies greater than 0.01 MeV. After irradiation, the units were retested at Fairchild. The Northrop reactor is a light-water pool-type TRIGA Mark F reactor. Dosimetry is sulfur-pellet type. No attempt was made to anneal damage.

Previous testing of linear microcircuits has been done by Messenger¹; however, none was tested in as great detail or on as complicated circuits as presented here. This report details the radiation effects on individual components and attempts to show how these effects can be correlated to overall circuit performance. Circuits tested were two operational amplifiers, the $\mu A702A$ and $\mu A709$, and two comparators, the $\mu A710$ and $\mu A711$.

KIT PART EVALUATION

A major part of the testing program was to evaluate the effects of radiation on the individual components of the integrated circuits. In the case of the linear integrated circuits, these included transistors, diode-connected transistors, zener diodes, and resistors. To evaluate individual components, a special metal mask was put on and individual components bonded out to the pins on a standard TO-5 package. Data were then taken on individual components before and after radiation. The most important components are the transistors. The NPN transistors consist of three basic types: (1) a high-beta, high break-

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down type used in the $\mu A709$, (2) a medium breakdown type used in the $\mu A702A$, and (3) a medium-beta, low breakdown gold-doped transistor used in the $\mu A710$ and $\mu A711$.

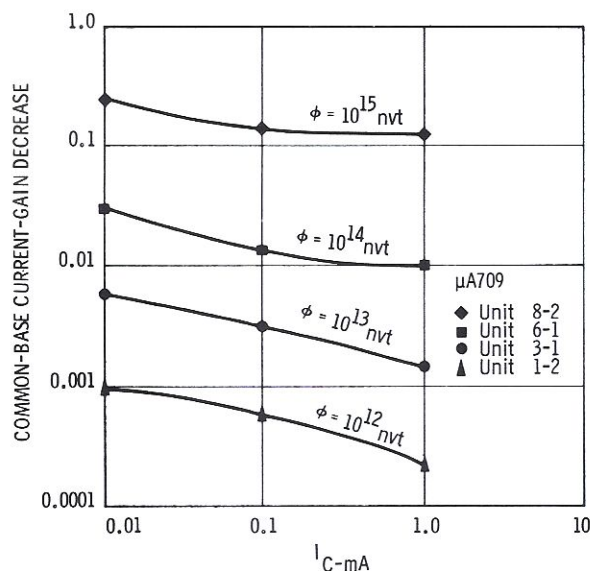


Fig. 1. Common-base current-gain degradation versus I_C at various levels of radiation for the $\mu A709$ kit part transistors.

A. Radiation Effects on Transistors.

1. Current Gain Degradation.

The most significant change in transistor parameters is, of course, the current-gain degradation. The transistors used in linear microcircuits are generally of a high-beta type. This is primarily due to a desire to minimize the input bias currents. The high beta is achieved partly by minimizing the base-width of the transistor which also results in an increase in f_T . The NPN transistors are made by the standard Fairchild Planar* epitaxial process with slightly different diffusion schedules to achieve high breakdown and high current-gain.

Table I shows the current gain before and after radiation of the high-beta, high-breakdown transistors used in the $\mu A709$, measured at $10 \mu A$. The current gain at $10 \mu A$ is important in the operation of the $\mu A709$ because the input stages are operated at collector currents of only $20 \mu A$. Table II shows the current gain of the $\mu A709$ kit parts at $100 \mu A$.

As can be seen by a comparison of Tables I and II, both pre- and post-radiation betas are higher at $100 \mu A$ than at $10 \mu A$. The lower pre-radiation beta is due to the fact that the emitter efficiency is lower at lower currents.² In addition, the emitter efficiency is lowered by irradiation.³ This can be shown by plotting the change in common-base current-gain versus I_C at various radiation levels. Fig. 1 is such a plot for the $\mu A709$ kit parts. More discussion of the current-gain degradation is given in the section on the circuit performance of $\mu A709$.

*Planar is a Fairchild patented process.

TABLE I

Current-Gain of $\mu A709$ Kit Part NPN Transistors Measured with $V_{CE} = 5V$ and $I_C = 10 \mu A$.

DEVICE NO.	RADIATION LEVEL				
	0	10^{12} nvt	10^{13} nvt	10^{14} nvt	10^{15} nvt
1-1	118	105			
1-2	164	140			
2-1	102	100			
2-2	67	65			
3-1	30		25		
3-2	69		50		
5-1	58			20	
5-2	82			20	
6-1	169			25	
6-2	112			23	
7-1	135				3.3
7-2	88				3.5
8-1	44				2.3
8-2	55				2.3

Table III shows the current gain before and after radiation of the medium beta low-breakdown transistor used in the $\mu A702A$. At this current level, the degradation of the $\mu A702A$ is somewhat greater than that of the $\mu A709$, as can be seen by a comparison of Table II and Table III.

TABLE II

Current-Gain of $\mu A709$ Kit Part Transistors Measured with $V_{CE} = 5V$ and $I_C = 100 \mu A$.

DEVICE NO.	RADIATION LEVEL				
	0	10^{12} nvt	10^{13} nvt	10^{14} nvt	10^{15} nvt
1-1	198	185			
1-2	248	218			
2-1	200	200			
2-2	190	188			
3-1	81		63		
3-2	118		90		
5-1	150			39	
5-2	193			42	
6-1	280			50	
6-2	210			45	
7-1	265				7.2
7-2	215				6.8
8-1	108				5.2
8-2	130				5.2

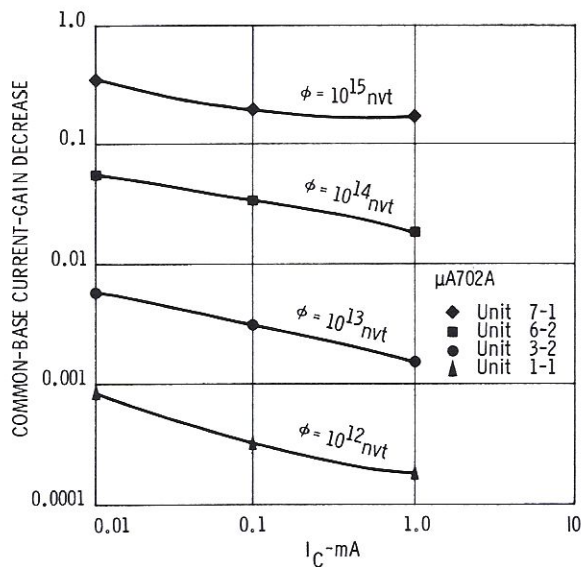


Fig. 2. Common-base current-gain degradation versus I_C at various levels of radiation for the $\mu A702A$ kit part transistors.

Data is given for the most critical application, $I_C = 100 \mu A$. This transistor shows the same degradation of emitter efficiency at low current levels as the $\mu A709$ transistor. Fig. 2 is the plot of alpha degradation versus I_C . Note the similarity to Fig. 1. This again shows that the emitter efficiency is degrading with radiation.

As previously mentioned, two of the circuits were integrated comparators. These units are gold-doped to increase

TABLE III

Current-Gain of $\mu A702A$ Kit Part Transistors
Measured with $V_{CE} = 5V$ and $I_C = 100 \mu A$.

DEVICE NO.	RADIATION LEVEL				
	0	10^{12} nvt	10^{13} nvt	10^{14} nvt	10^{15} nvt
1-1	72	70			
1-2	109	120*			
2-1	120	118			
2-2	145	133			
3-1	70		57		
3-2	102		75		
4-1	177		112		
4-2	162		105		
5-1	188			27	
5-2	213			27	
6-1	136			21	
6-2	147			22	
7-1	158				3.8
7-2	162				2.8
8-1	77				4.8
8-2	125				3.8

*Increase attributed to test error

TABLE IV

Current-Gain of $\mu A710$ Kit Part Transistors
Measured with $V_{CE} = 5V$ and $I_C = 1 mA$.

DEVICE NO.	RADIATION LEVEL				
	0	10^{12} nvt	10^{13} nvt	10^{14} nvt	10^{15} nvt
9-2	61	57			
10-1	72	73*			
10-2	62	61			
11-1	100		80		
11-2	87		70		
12-2	53		45		
13-1	71			29	
13-2	85			30	
14-1	60			21	
14-2	55			20	
15-1	74				4.1
15-2	75				4.2
16-1	81				4.3
16-2	86				4.4

*Increase attributed to test error

switching speed. The transistors used in the comparators are medium-beta low-breakdown transistors and were tested as part of the program. The common-emitter current gain for the test transistors are given in Table IV for $V_{CE} = 5V$ and $I_C = 1 mA$. Because of the low beta of these devices at low currents, they are usually not used below 1 mA. For purposes of comparison, the beta of the $\mu A709$ devices radiated are given at $I_C = 1 mA$ in Table V.

Comparing the results for gold-doped transistors with those of the $\mu A709$ transistors at 1 mA, there does not appear to be any appreciable benefit from the gold-doping as concerns radiation resistance. The $\mu A709$ devices all have higher betas after radiation. The only drawback of the $\mu A709$ device is that it saturates sooner, due to higher collector resistivity.

The kit part devices of the $\mu A711$ will not be discussed here, because the processing is identical to that of the $\mu A710$.

2. Leakage Current Effects.

Since radiation tends to decrease the lifetime on both sides of a p-n junction, the bulk leakage currents tend to increase.⁴ However, since surface leakage may predominate at low temperatures, low-temperature leakage currents may increase or decrease. The above is the result found in this study which agrees with earlier work on discrete transistors by Fitzgerald and Lauritzen.⁵

Table VI shows the room temperature I_{CBO} of $\mu A709$ kit parts before and after radiation. Notice that all leakages

TABLE V

Current-Gain of μ A709 Kit Part Transistors
Measured with $V_{CE} = 5V$ and $I_C = 1$ mA.

DEVICE NO.	RADIATION LEVEL				
	0	10^{12} nvt	10^{13} nvt	10^{14} nvt	10^{15} nvt
1-1	300	280			
1-2	340	315			
2-1	312	310			
2-2	342	340			
3-1	155		128		
3-2	172		140		
5-1	286			70	
5-2	313			71	
6-1	404			79	
6-2	343			85	
7-1	400				Sat
7-2	370				7.0
8-1	217				6.1
8-2	240				6.6

went down. This is probably due to changes in surface leakage. Table VII shows the I_{CBO} for the same units at $125^\circ C$ before and after radiation and indicates more clearly the increase in I_{CBO} due to lifetime damage. Since these increases are rather small even at high temperatures, they will not affect the operation of most linear circuits.

TABLE VI

Variation of Room Temperature I_{CBO} (nA)
with Radiation for μ A709 Kit Parts.
 I_{CBO} Measured with $V_{CB} = 5V$.

DEVICE NO.	RADIATION LEVEL			
	0	10^{12} nvt	10^{13} nvt	10^{14} nvt
4-1	0.10	0.016		
9-1	0.14	0.008		
11-1	0.10	0.02		
14-1	0.10	0.002		
19-1	0.10	0.002		
2-1	0.10		0.06	
3-1	0.16		0.01	
5-1	0.10		0.05	
15-1	0.10		0.017	
18-1	0.11		0.01	
6-1	0.15			0.075
7-1	0.2			0.05
10-1	0.12			0.04
16-1	1.2			0.9
17-1	0.15			0.07

TABLE VII

Variation of $125^\circ C$ I_{CBO} (nA) with Radiation for
 μ A709 Kit Parts. I_{CBO} Measured with $V_{CB} = 5V$.

DEVICE NO.	RADIATION LEVEL			
	0	10^{12} nvt	10^{13} nvt	10^{14} nvt
4-1	3.0	5.5		
9-1	4.2	2.2		
11-1	12.0	3.4		
14-1	3.5	2.1		
19-1	4.0	2.2		
2-1	4.0		18.0	
3-1	4.0		6.0	
5-1	12.0		14.0	
15-1	3.4		8.0	
18-1	3.5		5.5	
6-1	4.4			30.0
7-1	16.0			21.0
10-1	3.0			21.0
16-1	11.0			48.0
17-1	11.0			40.0

3. Voltage Breakdown.

Since radiation increases the resistivity, the breakdown voltage generally tends to increase on most transistors. However, some devices which are very close to punch-through may become punch-through devices and actually

TABLE VIII

LV_{CEO} of μ A709 Kit Parts After Radiation
Measured at 1 mA.

DEVICE NO.	RADIATION LEVEL			
	10^{12} nvt	10^{13} nvt	10^{14} nvt	10^{15} nvt
1-1	52			
1-2	50			
2-1	88			
2-2	53			
3-1		68		
3-2		69		
5-1			86	
5-2			88	
6-1			68	
6-2			70	
7-1				95
7-2				86
8-1				52
8-2				52

show a decrease in breakdown voltage. In the units tested, however, this did not occur. Table VIII gives the breakdown voltages for the $\mu A709$ devices after radiation. As can be seen, all are well above the required 40 volts.

TABLE IX

LV_{CEO} of $\mu A710$ Kit Parts After Radiation
Measured at 1 mA.

DEVICE NO.	RADIATION LEVEL			
	10^{12} nvt	10^{13} nvt	10^{14} nvt	10^{15} nvt
10-1	15.8			
10-2	15.2			
11-1		16.0		
11-2		15.6		
13-1			16.9	
13-2			16.8	
14-1			17.2	
14-2			17.2	
15-1				25.5
15-2				26.0
16-1				35.5
16-2				25.0

Breakdown voltages were also measured on the medium-beta low-breakdown gold-doped transistors. These were all well above the required 10 volts. The LV_{CEO} after radiation is given in Table IX.

4. PNP Transistors.

In the $\mu A709$ operational amplifier, there are two types of PNP transistors, a lateral and a vertical type. The effect of radiation on these PNP's will be discussed here.

The lateral PNP has been described in the literature.⁶ As made in the $\mu A709$, it is of necessity a wide-base device due to masking tolerances and side-diffusion. This wide base

TABLE X

Lateral PNP Beta Versus Radiation Measured
with $V_{CE} = 5V$ and $I_C = 100 \mu A$.

DEVICE NO.	RADIATION LEVEL			
	0	10^{12} nvt	10^{13} nvt	10^{14} nvt
1	8.1	6.4		
2	7.0	6.3		
3	5.8		2.0	
4	3.1		1.5	
6	9.1			0.2

gives it a low base-transport factor.⁷ In addition, due to the diffusion profiles, the emitter efficiency is low. The result is a very low beta unit. However, with proper circuit design, the lateral PNP can still be a useful, level-shifting device. This device did not have a discernible beta at 10^{15} nvt; therefore, data are given only to 10^{14} nvt. Table X gives the pre- and post-radiation beta of the lateral PNP at $100 \mu A$, the only current at which this device is used. As can be seen, the device is quite heavily damaged by radiation. Fortunately, the circuit can tolerate betas less than unity. More discussion of this point will be given later. Breakdown voltage of this device is quite high due to the impurity profiles. All devices had LV_{CEO} 's greater than 80 volts after radiation.

The vertical PNP, otherwise known as the substrate PNP, is a higher beta device than the lateral PNP, due to a smaller base width. This device is used as an output emitter follower transistor. This device also proved to be quite sensitive to radiation. Table XI gives the pre- and post-radiation betas at $I_C = 1$ mA. As can be seen, the typical device with a beta of 25 has a beta slightly less than two at 10^{14} nvt. This is also instructive in considering the parasitic beta of the substrate. The parasitic beta for a radiated device would be very low, one of the few good effects of radiation.

TABLE XI

Vertical PNP Beta Versus Radiation Measured
with $V_{CE} = 5V$ and $I_C = 1$ mA.

DEVICE NO.	RADIATION LEVEL				
	0	10^{12} nvt	10^{13} nvt	10^{14} nvt	10^{15} nvt
10	6.5	6.0			
12	25		14.3		
14	25			1.7	
15	26				.08
16	32				.13

5. Summary of Radiation Effects on Transistors.

In the preceding sections it has been shown that the predominant effect of radiation is to reduce the current-gain of the microcircuit transistors. This effect is more pronounced in the case of the two types of PNP transistors tested than in the case of the NPN transistors. Other transistor parameters degenerated very little and are not considered to affect circuit operation.

a. Diode-Connected Transistors.

In the design of linear integrated circuits, another commonly used component is the diode-connected transistor (DCT). The DCT is generally used as a biasing device and

TABLE XII

Diode Voltage in Volts of a μ A710 DCT
Versus Radiation Measured at 1 mA.

DEVICE NO.	RADIATION LEVEL				
	0	10 ¹² nvt	10 ¹³ nvt	10 ¹⁴ nvt	10 ¹⁵ nvt
9-2	0.721	0.721			
10-2	0.716	0.713			
11-2	0.706		0.708		
12-2	0.719		0.720		
13-2	0.698			0.710	
14-2	0.717			0.724	
15-2	0.711				0.773
16-2	0.712				0.765

sometimes as a voltage clamp. The DCT, rather than a collector-base diode, is employed because of its low leakage to the substrate.⁸ The most important characteristic of the DCT is its adherence to the ideal diode equation which may be expressed as:

$$I_d = I_S \exp(qV_d / kT),$$

where I_d = diode current

I_S = reverse saturation current

q = charge on the electron = 1.6×10^{-14} coulomb

k = Boltzmann's constant = 1.38×10^{-16} erg/deg K

T = temperature in deg K

V_d = diode voltage.

This is important because many bias currents in integrated circuits are calculated using this equation. Deviations from the ideal diode equation are due to, among others, contact resistance, base resistance, or collector resistance. The most important is collector resistivity, particularly for higher resistivity devices such as the μ A709. Table XII gives the diode voltage of a μ A710 DCT before and after radiation at $I_d = 1$ mA. Notice the large change at 10^{15} nvt.

Table XIII gives the diode voltage of a μ A709 DCT before and

TABLE XIII

Diode Voltage in Volts of a μ A709 DCT
Versus Radiation Measured at 1 mA.

DEVICE NO.	RADIATION LEVEL			
	0	10 ¹² nvt	10 ¹³ nvt	10 ¹⁴ nvt
2-1	0.720	0.719		
2-2	0.683	0.673		
3-1	0.699		0.696	
3-2	0.699		0.699	
5-1	0.685			0.697
5-2	0.692			0.699

after radiation. The significant difference is that, at 10^{15} nvt, the μ A709 diode voltage could not be read because the collector saturated at approximately 40 μ A. There is considerable scatter in the μ A709 data which makes a quantitative statement difficult even at 10^{14} nvt. However, the μ A710 does show a definite upward trend. This is attributed to base current drop across the base resistance. Both types, the μ A710 and the μ A709 DCT's, should be usable up to 10^{14} nvt. The μ A702A being similar to the μ A709 should also be usable to 10^{14} nvt.

b. Zener Diodes.

Zener diodes are used as level-shifting devices in the μ A710 and μ A711. To determine if any changes took place, the zener voltage was measured at 100 μ A. No significant changes occurred at 10^{15} nvt radiation.

TABLE XIV

Resistance Versus Radiation of Diffused Resistors
Measured at 0.1V and Radiated to 10^{15} NVT.

DEVICE NO.	BEFORE k Ω	AFTER	% CHANGE
702-151	2.067	2.117	+2.4
702-152	1.957	2.000	+2.1
702-161	2.351	2.402	+2.1
702-162	2.226	2.283	+2.5
709-151	26.40	27.10	+2.6
709-152	26.10	26.70	+2.2
709-161	35.31	36.50	+3.3
709-162	34.61	35.68	+3.0
710- 71	1.020	1.044	+2.3
710- 72	0.950	0.977	+2.8
710- 81	0.730	0.749	+2.5
710- 82	0.720	0.733	+1.8

c. Resistors.

Diffused resistors were tested from the μ A702A, μ A709, and μ A710. All resistors were measured at 0.1 volt to avoid parasitic diode effects. The resistors changed very little even at 10^{15} nvt. This is in some variation from earlier work⁹ and is attributed to a low sheet resistivity of approximately 100 ohms/square. Table XIV gives the pre- and post-radiation data for resistors radiated to a level of 10^{15} nvt. The first three numbers indicate the type of circuit in which the resistor is used. The change is fairly uniform from one device to the next and in no case is greater than 4 percent. The maximum ratio change is less than 1 percent for units on the same chip. Since linear microcircuits are designed to depend on ratios and not absolute values, and since radiation changes are small compared to initial component tolerances, resistance change with radiation is considered insignificant.

MICROCIRCUIT PERFORMANCE

In the previous section, a discussion was given of the sensitivity to radiation of the various microcircuit components. In this section, the circuit performance of the linear microcircuits will be discussed. The parameters under consideration include gain, offset, input bias current, and supply current.

A. Voltage Gain

It has been shown by Widlar¹⁰ that the differential voltage gain of a differential amplifier is given by:

$$A_V = \frac{I_C R_L}{kT/q},$$

where A_V = differential voltage gain

I_C = collector current in one side of the differential pair

R_L = the collector load resistance.

Notice that this equation does not include the effect of finite input impedance or the input impedance of the next stage. The effect of finite input impedance is to lower the effective input voltage. The effect of the input impedance of the next stage is to shunt the collector resistor. Both of these terms are dependent on the common-emitter current-gain, beta. Thus, although the basic voltage gain is independent of radiation, assuming I_C and R_L are constant, the actual voltage gain is beta dependent and therefore radiation de-

pendent. In like manner, the small-signal voltage gain of a grounded-emitter stage can be shown to be $qI_C R_L / kT$. This equation is also independent of beta. However, the same limitations apply.

Tables XV, a through d, show the voltage gain versus radiation of the microcircuits $\mu A702A$, $\mu A709$, $\mu A710$, and $\mu A711$. All data were taken at room temperature. Discussing the units in order, the $\mu A702A$ minimum gain is 1400 at room temperature. The $\mu A702C$ minimum gain is 1000. Notice that at 10^{14} nvt only two units failed to meet the specification of 1000 and only one missed by a large margin. This suggests that with selection, a minimum gain of 900 could be guaranteed at 10^{14} nvt. The technical reason for the gain reduction is probably the loading effect of the second stages, Q_4 and Q_5 , in the schematic given in Fig. 3.

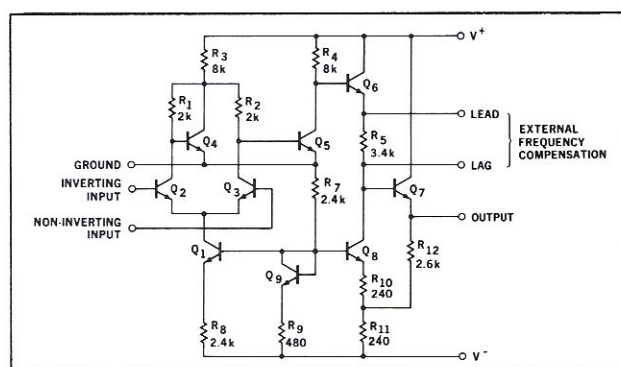


Fig. 3. $\mu A702A$ schematic.

TABLE XVa

Voltage Gain in V/V Versus Radiation of $\mu A702A$ Devices Measured at $V^+ = 12V$ and $V^- = -6V$, $R_L = 2K$.

DEVICE NO.	RADIATION LEVEL				
	0	10^{12} nvt	10^{13} nvt	10^{14} nvt	10^{15} nvt
1	2000	1700			
2	1400	1100			
3	1700	1500			
4	1500	1300			
6	1700		1350		
7	2200		1600		
8	1700		1400		
9	1700		1300		
11	1800			1000	
12	2000			1000	
13	1200			500	
14	1900			950	
16	1300				100
17	1400				25
18	1900				150
19	2000				25

Table XVb gives the gain versus radiation of the $\mu A709$ operational amplifier. Notice that data are only given to 3×10^{13} nvt. The reason for this is that the $\mu A709$ was

TABLE XVb

Voltage Gain in V/V Versus Radiation of $\mu A709$ Devices Measured at $V^+ = +15V$ and $V^- = -15V$ With No Load.

DEVICE NO.	RADIATION LEVEL			
	0	3×10^{12} nvt	10^{13} nvt	3×10^{13} nvt
1	45,000	45,000		
5	43,000	43,000		
7	43,000	43,000		
9	45,000	45,000		
4	44,000		43,000	
6	40,000		34,000	
8	43,000		43,000	
10	40,000		40,000	
13	44,000			30,000
14	44,000			40,000
15	45,000			40,000
19	45,000			43,000

tested early in the program and was not retested. The guaranteed minimum gain for the $\mu A709$ is 25,000 V/V. None of the units had a gain this low after radiation. Thus, at 3×10^{13} nvt all units met the specification for a premium device. There are a number of things which could cause gain reduction. Referring to the schematic in Fig. 4, Q_3 and Q_4 are biased at about $20 \mu A$; therefore

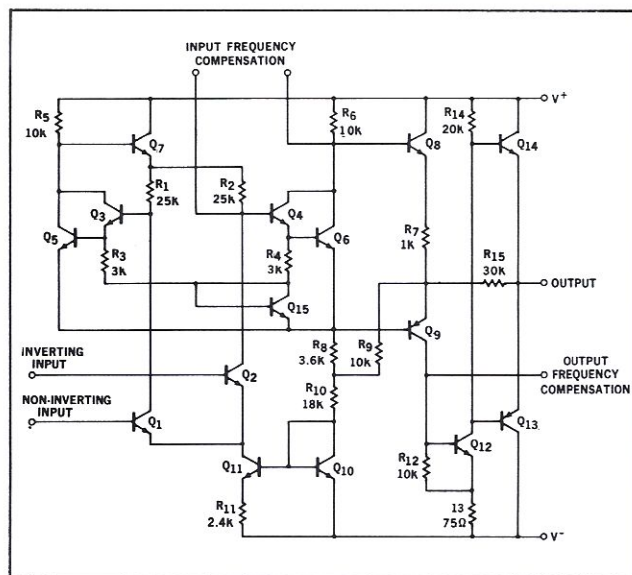


Fig. 4. $\mu A709$ schematic.

r_e is about 1250 ohms. The r_e of Q_5 and Q_6 is about 50 ohms, therefore Q_5 and Q_6 load down Q_3 and Q_4 where Q_5 and Q_6 have a beta less than 250 at $500 \mu A$. In a similar manner, Q_3 and Q_4 load down R_1 and R_2 . It is not expected that the later stages will affect the voltage gain because of the feedback network formed by R_{15} and R_7 . One radiation effect which may increase the gain is an increase in the

TABLE XVc

Voltage Gain in V/V of $\mu A710$ Devices Versus Radiation Measured at $V^+ = +12V$, $V^- = -6V$ and No Load.

DEVICE NO.	RADIATION LEVEL			
	0	10^{13} nvt	10^{14} nvt	10^{15} nvt
1	1400	1200		
2	2000	1800		
3	1600	1500		
9	1800		1200	
11	1400		800	
12	1500		850	
17	1600			60
18	1800			65
19	1800			30

diode voltage of the DCT, Q_{10} . This would increase the input stage bias current and the gain of the input stage. However, referring to Table XIII, the voltage change is very small at 10^{14} nvt, so the effect should be negligible.

Table XVc gives the voltage gain versus radiation of the $\mu A710$ comparator. This device had a good performance up to 10^{14} nvt. The data sheet minimum gain is 750 V/V and the worst gain was 800 V/V. A schematic diagram is given in Fig. 5. The reduction in gain is attributed primarily to

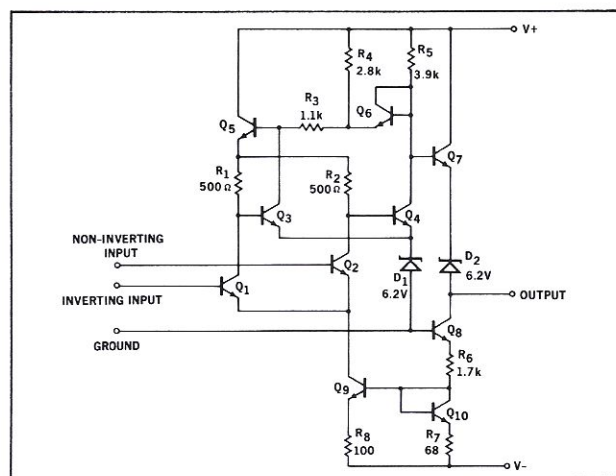


Fig. 5. $\mu A710$ schematic.

the loading of Q_3 and Q_4 upon R_1 and R_2 . Notice that the beta given in Table IV is approximately 25. This gives an input impedance to Q_3 and Q_4 of about 500 ohms which causes a 50-percent gain degradation which is roughly what is seen at 10^{14} nvt.

The schematic for the $\mu A711$ is given in Fig. 6. The causes

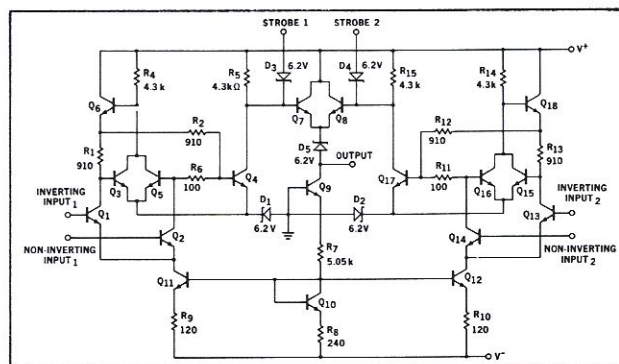


Fig. 6. $\mu A711$ schematic.

of degradation of this circuit are basically the same as that of the $\mu A710$. An important factor to note is that a signal appeared at the output of the $\mu A702A$, $\mu A710$, and $\mu A711$ devices that were radiated to 10^{15} nvt; thus there were no catastrophic failures even at this high level.

B. Input Bias Current

Probably the performance parameters most sensitive to radiation are the input bias current and its correlate, the input resistance. A short calculation will show that the change in input bias current is a function of the common-base current-gain degradation. The input bias current,

TABLE XVd

Voltage Gain in V/V of $\mu A711$ Devices Versus Radiation Measured at $V^+ = +12V$, $V^- = -6V$ and No Load.

DEVICE NO.	RADIATION LEVEL			
	0	10^{13} nvt	10^{14} nvt	10^{15} nvt
1	1400	1200		
2	1800	1500		
3	1800	1700		
4	1700	1500		
9	1700		800	
10	1800		800	
11	1800		900	
12	1800		1000	
19	2000			60
20	1400			40
21	1800			20
22	1700			60

I_B can be expressed as a function of the d-c beta, β , as:

$$I_B = I_C / \beta.$$

The change in input bias current $I_{B0} - I_{B0}$ can be expressed as

$$I_{B0} - I_{B0} = I_C / \beta_0 - I_C / \beta_0.$$

Adding and subtracting

$$I_{B0} - I_{B0} = I_C (1 - 1/\beta_0 - 1 + 1/\beta_0).$$

Assuming fairly high betas

$$I_{B0} - I_{B0} = I_C (\alpha_1 - \alpha_2)$$

$$I_B - I_{B0} = I_C \Delta \alpha,$$

Where Δ = the alpha degradation. Tables XVI, a through d, give input bias current versus radiation for micro-circuits $\mu A702A$, $\mu A709$, $\mu A710$, and $\mu A711$. All data are taken at room temperature.

Referring to the $\mu A702A$, the input stage is biased at approximately 200 μA ; hence an input bias current of 2 μA ; corresponds to a beta of 100. From Table I it is seen that the 100 μA beta at 10^{14} nvt is in the region of 40 to 50, therefore 4 to 5 μA is expected as the input bias current.

TABLE XVIa

Input Bias Current in μA for the $\mu A702A$ Devices Versus Radiation Measured at $V^+ = +12V$ and $V^- = -6V$.

DEVICE NO.	RADIATION LEVEL				
	0	10^{12} nvt	10^{13} nvt	10^{14} nvt	10^{15} nvt
1	3.4	3.7			
2	2.2	2.4			
3	3.1	3.2			
4	3.0	3.4			
6	5.4		6.3		
7	2.9		4.1		
8	3.8		4.8		
9	2.8		3.8		
11	1.7			5.8	
12	1.7			5.5	
13	8.8			16.0	
14	2.0			6.0	
16	9.0				44.0
17	4.5				19.5
18	1.8				22.5
19	2.3				19.5

This is approximately the value obtained on three out of four units. The other unit was a low beta device before radiation and, as such, degraded more after radiation. For reference, the maximum input bias current of the $\mu A702A$ is 10 μA .

The input bias current of the $\mu A709$ versus radiation is given in Table XVIb. The input stage is biased at 20 μA ,

TABLE XVIb

Input Bias Current in μA for the $\mu A709$ Devices Versus Radiation Measured at $V^+ = +15V$ and $V^- = -15V$.

DEVICE NO.	RADIATION LEVEL			
	0	3×10^{12} nvt	10^{13} nvt	3×10^{13} nvt
1	0.12	0.14		
2	0.16	0.19		
3	0.15	0.18		
5	0.09	0.12		
4	0.15		0.27	
6	0.12		0.22	
8	0.07		0.13	
10	0.20		0.30	
13	0.13			0.30
14	0.13			0.32
15	0.21			0.40
16	0.11			0.29

hence an input bias current of $0.1 \mu\text{A}$ corresponds to a beta of 200. Extrapolating the data of Table I, a beta of 50 to 75 should be expected at 3×10^{13} nvt at $20 \mu\text{A } I_C$. This corresponds to an input bias current of 0.25 to $0.4 \mu\text{A}$. This is the region of the actual measured currents. For reference purposes, the maximum I_b on the μA709 data sheet is $0.5 \mu\text{A}$.

TABLE XVIc

Input Bias Current in μA for the μA710 Devices
Versus Radiation Measured at $V^+ = +12\text{V}$ and
 $V^- = -6\text{V}$.

DEVICE NO.	RADIATION LEVEL			
	0	10^{13} nvt	10^{14} nvt	10^{15} nvt
1	29.0	31.2		
2	13.0	19.2		
3	11.0	14.5		
4	9.0	9.1		
9	23.0		66.7	
11	33.0		79.8	
12	29.0		79.6	
17	8.2			225
18	49.0			415
19	19.0			233
20	42.0			361

Table XVIc shows the input bias current versus radiation for the μA710 comparator. The input stage is biased at 1 mA, hence an input bias current of $10 \mu\text{A}$ corresponds to a beta of 100. Referring to Table IV, beta after radia-

TABLE XVIId

Input Bias Current in μA for the μA711 Devices
Versus Radiation Measured at $V^+ = +12\text{V}$ and
 $V^- = -6\text{V}$.

DEVICE NO.	RADIATION LEVEL			
	0	10^{13} nvt	10^{14} nvt	10^{15} nvt
1	16.5	19.1		
2	14.3	17.8		
3	12.5	14.6		
4	9.6	11.0		
9	12.7		27.8	
10	10.9		25.0	
11	11.0		27.2	
12	7.0		16.7	
19	9.1			74.0
20	21.4			87.3
21	24.9			100.0
22	14.9			84.6

tion ranges from 20 to 30, which corresponds to input bias currents of 30 to $50 \mu\text{A}$. However, the units tested ran 65 to $80 \mu\text{A}$. This is attributed to the fact that all the units tested had lower betas than the kit part transistors. The data sheet maximum input bias current for the μA710 is $75 \mu\text{A}$.

The μA711 is virtually identical to the μA710 . Notice the lower currents at 10^{14} nvt due to higher initial beta. The data sheet limit for the μA711 is $75 \mu\text{A}$.

C. Voltage Offset

The voltage offset of a differential pair, ΔV_{be} , is given by Widlar¹¹ as:

$$\Delta V_{be} = kT/q \ln \frac{I_{C1}}{I_{C2}} + kT/q \ln (I_{S2}/I_{S1}),$$

TABLE XVIIa

Voltage Offset in mV Versus
Radiation for μA702A Devices.

DEVICE NO.	RADIATION LEVEL				
	0	10^{12} nvt	10^{13} nvt	10^{14} nvt	10^{15} nvt
1	+0.8	+0.7			
2	+2.8	+2.5			
3	+0.9	+0.9			
4	-0.8	-0.8			
5	-2.4	-2.0			
6	+0.1		+0.3		
7	+2.0		+1.9		
8	+2.6		+2.7		
9	-1.0		-1.0		
10	-0.6		-0.8		
11	-0.9			-1.4	
12	+0.9			+0.5	
13	-1.8			-3.4	
14	+0.6			+0.4	
15	-0.6			-1.2	
16	+2.0				-6.2
17	-0.4				-6.5
18	-2.9				-6.2
19	-0.2				-4.6
20	-1.8				-7.2

where I_{S1} and I_{S2} are the reverse saturation currents of the differential pair. Since a differential pair usually operates with identical collector currents, the voltage offset is mostly due to the mismatch in I_{S1} and I_{S2} . Although radiation tends to increase these, they should track together and the ratio should remain unchanged. Tables XVII, a through

d, show the voltage offset change versus radiation on the $\mu A702A$, $\mu A709$, $\mu A710$, and $\mu A711$. All data are taken at room temperature. Only one $\mu A702A$ changed more than 1 millivolt up to 10^{14} nvt. All $\mu A711$'s and $\mu A710$'s changed

TABLE XVIIb

Voltage Offset in mV Versus
Radiation for $\mu A709$ Devices.

DEVICE NO.	RADIATION LEVEL			
	0	3×10^{12} nvt	10^{13} nvt	3×10^{13} nvt
5	-0.3	-0.3		
7	+2.1	+2.2		
9	-0.6	-0.5		
2	-3.0	-3.0		
6	-0.2		-0.2	
8	-0.3		-0.2	
4	-0.4		-0.4	
11	-0.8		-0.8	
15	-1.0			-1.0
19	+1.8			+1.8
13	-1.5			-1.4
14	-0.6			-0.6

less than 1 millivolt. All $\mu A709$'s changed less than 0.2 millivolt but they were tested only to 3×10^{13} nvt. Since other parameters show much worse degradation, voltage offset change is considered insignificant.

D. Current Offset

Since the current offset, I_{OS} , is a function of the beta mis-

TABLE XVIIc

Voltage Offset in mV Versus
Radiation for $\mu A710$ Devices.

DEVICE NO.	RADIATION LEVEL			
	0	10^{13} nvt	10^{14} nvt	10^{15} nvt
1	+6.2	+6.2		
2	+6.0	+6.0		
3	+3.6	+3.6		
4	-6.4	-6.3		
9	+5.7		+6.0	
11	+1.4		+1.3	
12	+5.9		+6.1	
17	+1.1			-1.3
18	+2.5			+4.6
19	+2.0			-1.5
20	-0.1			-7.6

TABLE XVIIId

Voltage Offset in mV Versus
Radiation for $\mu A711$ Devices.

DEVICE NO.	RADIATION LEVEL			
	0	10^{13} nvt	10^{14} nvt	10^{15} nvt
1	+1.2	+1.2		
2	+0.4	+0.4		
3	-0.2	-0.15		
4	-4.1	-4.1		
9	+0.6		+1.0	
10	-1.4		-1.0	
11	+0.5		+0.8	
12	+0.6		+1.2	
19	-0.2			+6.4
20	+0.8			+8.6
21	+2.2			Sat
22	-1.4			+0.2

match of the input pair, it would be expected that I_{OS} would increase with radiation. This is usually the case; however, a great number of exceptions were seen. The $\mu A702A$ data sheet maximum is $2 \mu A$. No unit was worse than $1 \mu A$ at

TABLE XVIIId

Input Offset Current in μA Versus
Radiation for the $\mu A702A$ Devices.

DEVICE NO.	RADIATION LEVEL				
	0	10^{12} nvt	10^{13} nvt	10^{14} nvt	10^{15} nvt
1	0	+ .25			
2	+ .05	+ .35			
3	- .45	+ .35			
4	- .85	+ .25			
5	+ .65	+ .25			
6	-1.80		- .50		
7	+ .10		+ .15		
8	+1.80		+ .75		
9	-1.05		- .05		
11	+ .35			- .10	
12	- .05			+ .20	
13	-1.75			-1.00	
14	+ .45			+ .55	
16	+5.10				- .40
17	- .50				- .45
18	+ .30				-1.00
19	- .40				- .50

TABLE XVIIIb

Input Offset Current in nA Versus
Radiation for the μ A709 Devices.

DEVICE NO.	RADIATION LEVEL			
	0	3×10^{12} nvt	10^{13} nvt	3×10^{13} nvt
1	+80	+70		
5	0	0		
7	+90	+90		
9	+70	0		
6	-40		-40	
8	+20		+20	
4	-20		-20	
11	-10		+10	
15	0			0
19	+20			+ 40
13	-20			- 40
14	-90			-110

10^{14} nvt. The μ A709 data sheet maximum is 200 nA. No unit is worse than 100 nA. The μ A710 data sheet maximum is 10μ A. No unit is worse than 6.5μ A at 10^{14} nvt. The μ A711 data sheet maximum is 10μ A. No unit is worse than 4μ A up to 10^{14} nvt.

The reason that the current offset does not show a great increase is that, after radiation, high beta units have a greater percentage change than low beta units. This tends to equalize the base current and minimize the offset current. Tables XVIII, a through d, give the offset current for

TABLE XVIIIc

Input Offset Current in μ A Versus
Radiation for the μ A710 Devices.

DEVICE NO.	RADIATION LEVEL			
	0	10^{13} nvt	10^{14} nvt	10^{15} nvt
1	+1.0	-1.5		
2	+1.0	-2.0		
3	0	- .5		
4	-3.0	+3.0		
9	+4.0		+6.5	
11	+2.0		+2.5	
12	+3.0		+6.5	
17	0			+2.5
18	+13.5			-19.5
19	+1.0			+4.0
20	-2.5			+11.6

TABLE XVIIIId

Input Offset Current in μ A Versus
Radiation for the μ A711 Devices.

DEVICE NO.	RADIATION LEVEL			
	0	10^{13} nvt	10^{14} nvt	10^{15} nvt
1	-1.0	-1.0		
2	-0.5	+1.0		
3	-1.5	-1.5		
4	-0.5	-1.0		
9	0		0	
10	0		0	
11	-0.5		0	
12	-1.0		-1.0	
19	+1.0			+5.0
20	0			+11.0
21	+1.0			Sat
22	-2.0			-1.5

the units tested versus radiation. All data are taken at room temperature.

E. Power Dissipation

Since the supply current drain is a function of a number of resistors, it is expected that the power dissipation should

TABLE XIXa

Positive Supply Current in mA Versus Radiation of
the μ A702A Devices Measured at $V^+ = +12V$ and
 $V^- = -6V$.

DEVICE NO.	RADIATION LEVEL				
	0	10^{12} nvt	10^{13} nvt	10^{14} nvt	10^{15} nvt
1	7.1	6.9			
2	8.4	6.8			
3	6.8	6.5			
4	7.6	6.7			
6	7.5		7.0		
7	8.5		6.7		
8	7.0		6.4		
9	7.2		6.1		
11	7.0			6.6	
12	7.2			6.7	
13	8.0			6.8	
14	7.8			6.8	
16	7.4				5.1
17	7.6				5.1
18	7.3				4.8
19	6.9				5.0

TABLE XIXb

Positive Supply Current in mA Versus Radiation of the μ A709 Devices Measured at $V^+ = +15V$ and $V^- = -15V$.

DEVICE NO.	RADIATION LEVEL			
	0	3×10^{12} nvt	10^{13} nvt	3×10^{13} nvt
1	3.45	3.53		
5	3.73	3.28		
7	4.25	4.31		
9	3.40	3.45		
6	3.41		3.48	
8	2.72		2.71	
4	4.16		4.28	
11	3.20		3.28	
15	3.64			3.83
19	4.05			4.18
13	3.45			3.51
14	3.07			3.08

decrease with increasing radiation. This is indeed the case, but the decreases are somewhat larger than expected, except in the case of the μ A709. This is attributed to a change in the output voltage at which power dissipation is measured.

Table XIX, a through d, gives the power dissipation versus radiation of the units tested. All data are taken at room temperature.

TABLE XIXc

Power Dissipation in mW Versus Radiation of the μ A710 Devices Measured at $V^+ = +12V$ and $V^- = -6V$.

DEVICE NO.	RADIATION LEVEL			
	0	10^{13} nvt	10^{14} nvt	10^{15} nvt
1	94.2	94.5		
2	81.6	81.6		
3	83.4	85.1		
4	85.1	86.0		
9	109.0		107.5	
11	96.4		93.5	
12	99.0		96.5	
17	204.0			169.7
18	100.0			72.1
19	64.4			45.7
20	96.0			70.2

TABLE XIXd

Power Dissipation in mW Versus Radiation of the μ A711 Devices Measured at $V^+ = +12V$ and $V^- = -6V$.

DEVICE NO.	RADIATION LEVEL			
	0	10^{13} nvt	10^{14} nvt	10^{15} nvt
1	137	132		
2	143	129		
3	159	153		
4	109	100		
9	127		117	
10	133		133	
11	130		116	
12	120		105	
19	130			100
20	146			109
21	147			106
22	147			109

SUMMARY AND CONCLUSIONS

It has been shown that the predominant effect of radiation on microcircuit components is the degradation of current-gain. Both base-transport factor and emitter efficiency are reduced. Resistors change less than 4 percent at 10^{15} nvt. Other changes are insignificant.

In regards to circuit parameters, the largest change is seen in the input bias current. The amount of change in voltage gain is a function of beta dependence and feedback. Voltage offsets and current offsets change little at levels at which other parameters are largely degraded. Power dissipation is generally reduced. Most units were within specification at 10^{14} nvt. It is believed that microcircuits compare favorably to discrete components in regards to fast neutron radiation.

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